Towards a Complete Experiment in Vector-Meson Photoproduction from FROST

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Florida State University

CLAS Collaboration Meeting

02/26/2016

Outline

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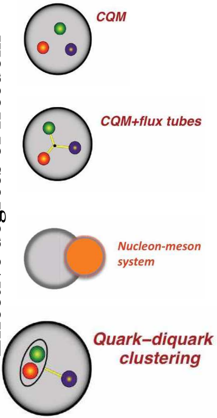
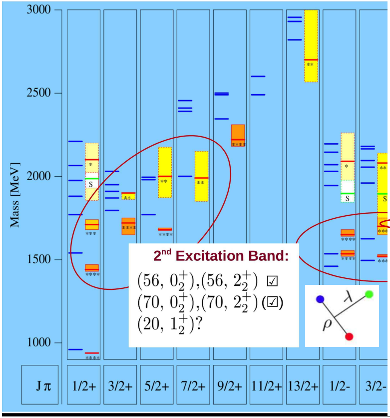
1. Introduction
   - Motivation
2. Data Analysis and Results
   - $p\omega$ Reaction, Single- & Double-Polarization Observables
   - $p\pi^+\pi^-$ Reaction, Single Polarization Observables
3. Summary and Outlook

Why Baryon Spectroscopy?

[1] R. Bradford *et al.* (CLAS), PRC **75**, 035205 (2007), Observables C_x, C_z from $\vec{\gamma} p \to K^+ \vec{\Lambda}$
[2] Fits: BnGa Model, V.A. Nikonov *et al.*, Phy. Lett. B **662**, 245 (2008)

Effective degrees of freedom





N^*	J^P $(L_{2I,2J})$	2010	2012
$N(1440)$	$1/2^+$ (P_{11})	****	****
$N(1520)$	$3/2^-$ (D_{13})	****	****
$N(1535)$	$1/2^-$ (S_{11})	****	****
$N(1650)$	$1/2^-$ (S_{11})	****	****
$N(1675)$	$5/2^-$ (D_{15})	****	****
$N(1680)$	$5/2^+$ (F_{15})	****	****
$N(1685)$			*
$N(1700)$	$3/2^-$ (D_{13})	***	***
$N(1710)$	$1/2^+$ (P_{11})	***	***
$N(1720)$	$3/2^+$ (P_{13})	****	****
$N(1860)$	$5/2^+$		**
$N(1875)$	$3/2^-$		***
$N(1880)$	$1/2^+$		**
$N(1895)$	$1/2^-$		**
$N(1900)$	$3/2^+$ (P_{13})	**	***
$N(1990)$	$7/2^+$ (F_{17})	**	**
$N(2000)$	$5/2^+$ (F_{15})	**	**
~~$N(2080)$~~	D_{13}	**	
~~$N(2090)$~~	S_{11}	*	
$N(2040)$	$3/2^+$		*
$N(2060)$	$5/2^-$		**
$N(2100)$	$1/2^+$ (P_{11})	*	*
$N(2120)$	$3/2^-$		**
$N(2190)$	$7/2^-$ (G_{17})	****	****
~~$N(2200)$~~	D_{15}	**	
$N(2220)$	$9/2^+$ (H_{19})	****	****

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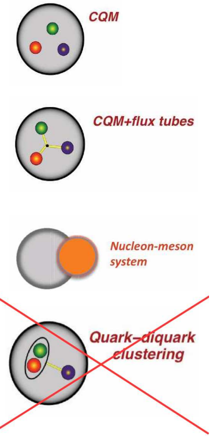

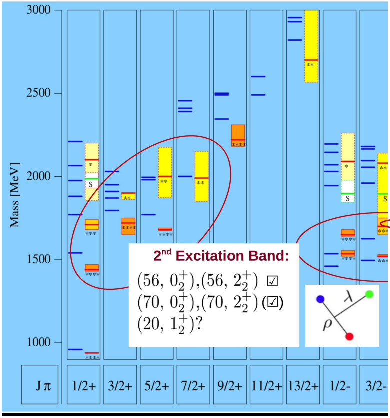

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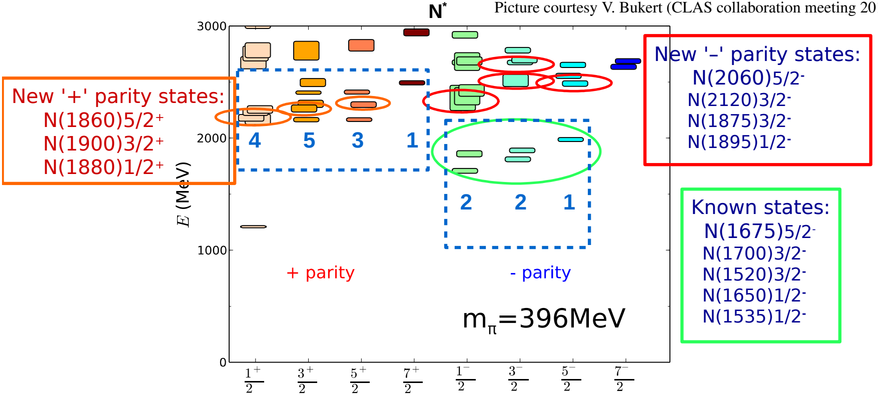
~~$N(2200)$~~	D_{15}	**	
$N(2220)$	$9/2^+\ (H_{19})$	****	****

$N(1900)3/2^+$ (which can be assigned as a member of the quartet of $(\mathbf{70},\ 2_2^+)$) cannot be accommodated in the naive quark-diquark picture, both oscillators need to be excited.[1],[2]

Baryon Spectrum with LQCD

R. Edwards *et al.* Phys. Rev. D **84** 074508 (2011)
Picture courtesy V. Bukert (CLAS collaboration meeting 2015)



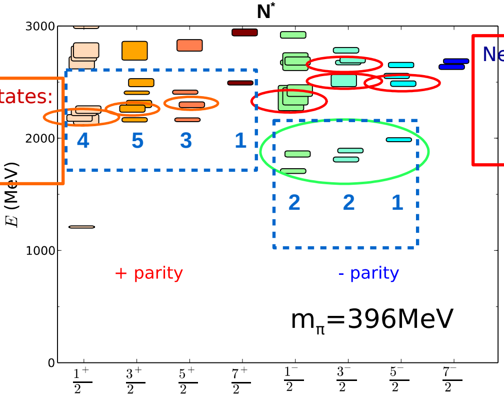
- - - LQCD manifests broad features of $SU(6) \otimes O(3)$ symmetry.

New states accommodated in LQCD calculations (ignoring mass scale) with J^P values consistent with CQM.

Baryon Spectrum with LQCD

More predicted states than experimentally observed. Lot more yet to be learnt!

New '+' parity states:
N(1860)5/2+
N(1900)3/2+
N(1880)1/2+



New '–' parity states:
N(2060)5/2-
N(2120)3/2-
N(1875)3/2-
N(1895)1/2-

Known states:
N(1675)5/2-
N(1700)3/2-
N(1520)3/2-
N(1650)1/2-
N(1535)1/2-

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Study of N^* to Vector Meson Decay Modes

Vector meson (ω, ρ, ϕ) decay modes have mostly remained unexplored. Vast pool of information yet to be unearthed:

- For a better understanding of known resonances, it is essential to study their vector meson decay modes.
- They carry the same J^{PC} as the photon so it is highly expected that they play an important role in the baryon spectrum.
- This talk will focus on $\gamma p \to p\pi^+\pi^-$ and $\gamma p \to p\omega \to p\pi^+\pi^-(\pi^0)$ reactions. The former gives information on $N^* \to p\rho$ which is difficult to study directly due to the broad nature of ρ.
- Ongoing analysis on $\gamma p \to p\phi$ cross section from CLAS-g12 (A. Hurley, FSU).

			Status as seen in —							
Particle J^P	Status overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$N(1700)\,3/2^-$	***	***	**	*			*	*	*	***
$N(1710)\,1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)\,3/2^+$	****	****	***	***			**	**	**	*
$N(1860)\,5/2^+$	**	**							*	*
$N(1875)\,3/2^-$	***	*	***			**	***	**		***
$N(1880)\,1/2^+$	**	*	*		**		*			
$N(1895)\,1/2^-$	**	*	**	**			**	*		
$N(1900)\,3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)\,7/2^+$	**	**	**					*		
$N(2000)\,5/2^+$	**	*	**	**			**	*	**	
$N(2040)\,3/2^+$	*									
$N(2060)\,5/2^-$	**	**	**	*				**		
$N(2100)\,1/2^+$	*									
$N(2150)\,3/2^-$	**	**	**				**			**
$N(2190)\,7/2^-$	****	****	***			*	**		*	
$N(2220)\,9/2^+$	****	****								
$N(2250)\,9/2^-$	****	****								
$N(2600)\,11/2^-$	***	***								
$N(2700)\,13/2^+$	**	**								

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$N(1710)\,1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)\,3/2^+$	****	****	***	***			**	**	**	*
$N(1860)\,5/2^+$	**	**							*	*
$N(1875)\,3/2^-$	***	*	***			**	***	**		***
$N(1880)\,1/2^+$	**	*	*		**		*			
$N(1895)\,1/2^-$	**	*	**	**			**	*		
$N(1900)\,3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)\,7/2^+$	**	**	**					*		
$N(2000)\,5/2^+$	**	*	**	**			**	*	**	
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	Status		Status as seen in —							
Particle J^P	overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$N(1700)\,3/2^-$	***	***	**	*			*	*	*	***
$N(1710)\,1/2^+$	***	***	***	***		**	***	**	*	**
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$N(1895)\,1/2^-$	**	*	**	**			**	*		
$N(1900)\,3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)\,7/2^+$	**	**	**					*		
$N(2000)\,5/2^+$	**	*	**	**			**	*	**	
$N(2040)\,3/2^+$	*									
$N(2060)\,5/2^-$	**	**	**	*				**		
$N(2100)\,1/2^+$	*									
$N(2150)\,3/2^-$	**	**	**				**			**
$N(2190)\,7/2^-$	****	****	***			*	**		*	
$N(2220)\,9/2^+$	****	****								
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$N(1990)\,7/2^+$	**	**	**					*		
$N(2000)\,5/2^+$	**	*	**	**			**	*	**	
$N(2040)\,3/2^+$	*									
$N(2060)\,5/2^-$	**	**	**	*				**		
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$N(2150)\,3/2^-$	**	**	**				**			**
$N(2190)\,7/2^-$	****	****	***			*	**		*	
$N(2220)\,9/2^+$	****	****								
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Why are Spin Observables Important?

Baryon resonances are broad and overlapping so peak hunting is difficult. Need more observables in addition to cross sections to disentangle the resonances.

Why are Spin Observables Important?

Polarization observables are essential for the determination of the scattering amplitudes with minimal ambiguities $\rightarrow$ 'reveal' the baryon resonances.

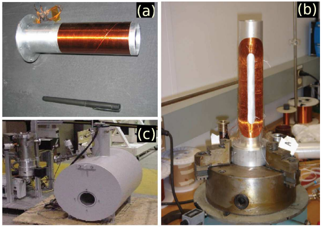
E.g., in single meson photoproduction:

$$\sigma_{\text{total}} = \sigma_{\text{unpol.}}[1 - \delta_l \, \mathbf{\Sigma} \cos(2\phi) + \Lambda_x \, (-\delta_l \, \mathbf{H} \sin(2\phi) + \delta_\odot \, \mathbf{F}) - \Lambda_y \, (-\mathbf{T} + \delta_l \, \mathbf{P} \cos 2\phi) - \Lambda_z \, (-\delta_l \, \mathbf{G} \sin(2\phi) + \delta_\odot \, \mathbf{E}) + ...]$$

$\delta_\odot(\delta_l)$: degree of beam pol.
Λ : degree of target pol.

Spin Observables for $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$ & $p\omega$ @ FROST

Getting close to a ‘complete experiment’!



Data taking: Oct 2007 - Jan 2008 (g9a)
Mar. - Aug 2010 (g9b)
Target: **FRO**zen **S**pin butanol **T**arget
Target pol.: Longitudinal (g9a run)/
Transverse (g9b run)
Photon pol.: Linear/Circular

$p\omega$:

Beam \ Target	Transversely Pol.	Longitudinally Pol.
Linearly Pol.	Σ, T, H, P	Σ, G
Circularly Pol.	F, T	E

W range covered $\sim$ 1.5 to 2.3 GeV

Prelim. results (Priyashree, FSU)
(Analysis note under review)

$p\pi^+\pi^-$:

Beam \ Target	Transversely Pol.	Longitudinally Pol.
Linearly Pol.	$P^{s,c}_{x,y}$, $P_{x,y}$, $I^{s,c}$	$P^{s,c}_{z}$, P_{z}, $I^{s,c}$
Circularly Pol.	$P^{\odot}_{x,y}$, $P_{x,y}$, $I^{\odot}$	$P^{\odot}_{z}$, P_{z}, $I^{\odot}$

Prelim. results available
(FSU, USC)
Data acquired

Outline

Data Selection and Analysis

- **Topologies for $\mathrm{p}\pi^+\pi^-$:**
  $\vec{\gamma}\vec{p} \to p\pi^+$ (missing π^-)
  $\vec{\gamma}\vec{p} \to p\pi^-$ (missing π^+)
  $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$ (no missing particle)
  The observables are weighted avg. over topologies.
- **Topology for $\mathrm{p}\omega$ (89% branching fraction):**
  $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$(missing π^0)
  Topology identified using Kinematic fitting.
- **Standard cuts & corrections:** vertex cut, photon selection, β cuts, E-p corrections.
- **Event-based method**[1] for signal-background separation.
- **Event-based maximum likelihood method**[2] for extracting polarization observables.

Data Selection and Analysis

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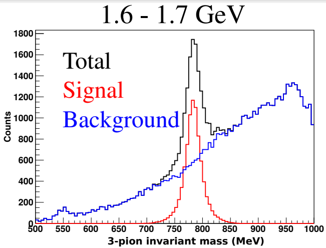

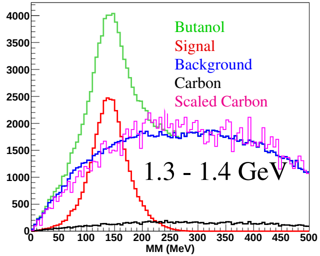

[1] M. Williams *et al.*, JINST 4 (2009) P10003

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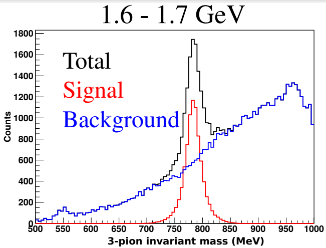
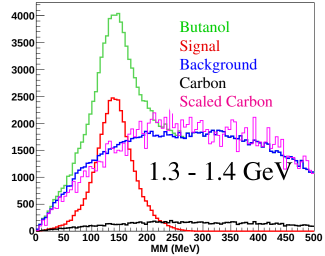




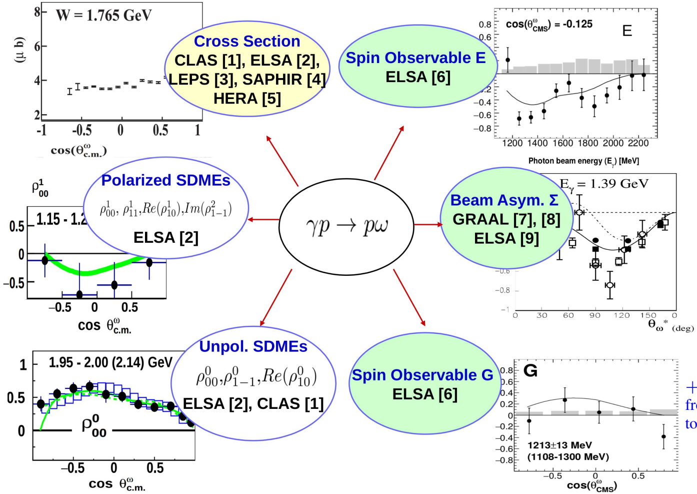
[1] M. Williams *et al.*, JINST 4 (2009) P10003
[2] D G Ireland, CLAS Note 2011-010

Results

Results in $\vec{\gamma}\vec{p} \to p\omega$

Published Results in $\gamma p \to p\omega$

Isospin filter (sensitive to N^* only), reduces complexity



[1] Williams *et al.*, PRC **80**, 065208 (2009)
[2] Wilson *et al.*, arXiv:1508.01483 (2015)
[3] Sumihama *et al.*, PRC **80**, 052201 (2009)
[4] Barth *et al.*, EPJ A **18**, 117 (2003)
[5] Wolf, Rept. Prog. Phys. **73**, 116202 (2010)
[6] Eberhardt *et al.*, arXiv:1504.02221 (2015)
[7] Vegna *et al.*, PRC **91**, 065207 (2015)
[8] Ajaka *et al.*, PRL **96**, 132003 (2006)
[9] F. Klein *et al.*, PRD **78**, 117101 (2008)

+ High quality polarized SDMEs from CLAS, Brian Vernarsky (CMU), to be published soon.

Partial Wave Analysis of $\gamma p \to p\omega$ Observables

Pol. SDMEs and Σ were crucial to understand the t-channel background: Major contribution from pomeron exchange mechanism.

BnGa PWA 2016 (coupled-channel) using ELSA data

Notable contribution — Suggestive evidence

CLAS PWA 2009

Notable contribution — Suggestive evidence

I. Denisenko *et al.*, Phys. Lett. B (2016)
M. Williams *et al.*, PRC **80**, 065208 (2009)

* rating in PDG 2014

Particle J^P	overall	$N\omega$
$N(1680)\ 5/2^+$	****	
$N(1685)\ ?^?$	*	
$N(1700)\ 3/2^-$	***	
$N(1710)\ 1/2^+$	***	**
$N(1720)\ 3/2^+$	****	
$N(1860)\ 5/2^+$	**	
$N(1875)\ 3/2^-$	***	**
$N(1880)\ 1/2^+$	**	
$N(1895)\ 1/2^-$	**	
$N(1900)\ 3/2^+$	***	**
$N(1990)\ 7/2^+$	**	
$N(2000)\ 5/2^+$	**	
$N(2040)\ 3/2^+$	*	
$N(2060)\ 5/2^-$	**	
$N(2100)\ 1/2^+$	*	
$N(2150)\ 3/2^-$	**	
$N(2190)\ 7/2^-$	****	*
$N(2220)\ 9/2^+$	****	
$N(2250)\ 9/2^-$	****	

Partial Wave Analysis of $\gamma p \to p\omega$ Observables

Pol. SDMEs and Σ were crucial to understand the t-channel background: Major contribution from pomeron exchange mechanism.

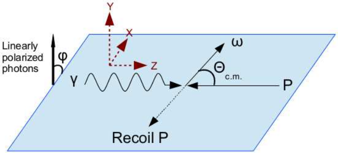
Need more polarization observables, in particular to understand W$>$ 2 GeV region:

- N($\sim$ 2.2 GeV) Uncertain J^P: $1/2^-, 3/2^+, 3/2^-$ or $5/2^+$?$^?$
- N($>$ 2.1 GeV) $7/2^-$?

* rating in PDG 2014

Particle J^P	overall	$N\omega$
$N(1680)\,5/2^+$	****	
$N(1685)\quad ?^?$	*	
$N(1700)\,3/2^-$	***	
$N(1710)\,1/2^+$	***	**
$N(1720)\,3/2^+$	****	
$N(1860)\,5/2^+$	**	
$N(1875)\,3/2^-$	***	**
$N(1880)\,1/2^+$	**	
$N(1895)\,1/2^-$	**	
$N(1900)\,3/2^+$	***	**
$N(1990)\,7/2^+$	**	
$N(2000)\,5/2^+$	**	
$N(2040)\,3/2^+$	*	
$N(2060)\,5/2^-$	**	
$N(2100)\,1/2^+$	*	
$N(2150)\,3/2^-$	**	
$N(2190)\,7/2^-$	****	*
$N(2220)\,9/2^+$	****	
$N(2250)\,9/2^-$	****	

Beam Asymmetry Σ in $\vec{\gamma}p \to p\omega$

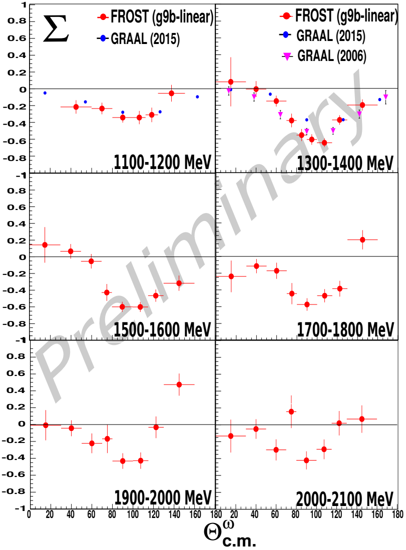


ω reconstructed from $\pi^+\pi^-(\pi^0)$

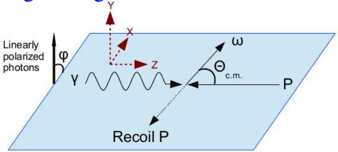
$$\sigma = \sigma_0[1 - \Sigma\ \delta_l \cos(2\phi) + \Lambda\cos(\alpha)(-\delta_l \mathbf{H}\sin(2\phi) + \delta_\odot \mathbf{F}) - \Lambda\sin(\alpha)(-\mathbf{T} + \delta_l \mathbf{P}\cos(2\phi))] - \Lambda_z(-\delta_l \mathbf{G}\sin(2\phi) + \delta_\odot \mathbf{E})]$$

$\delta_\odot(\delta_l)$: degree of beam pol.
Λ : degree of target pol.

Beam Asymmetry Σ in $\vec{\gamma}p \to p\omega$



FROST: transversely polarized target
GRAAL: unpolarized target
Good agreement between FROST and GRAAL (2006) results. New results at high energies.

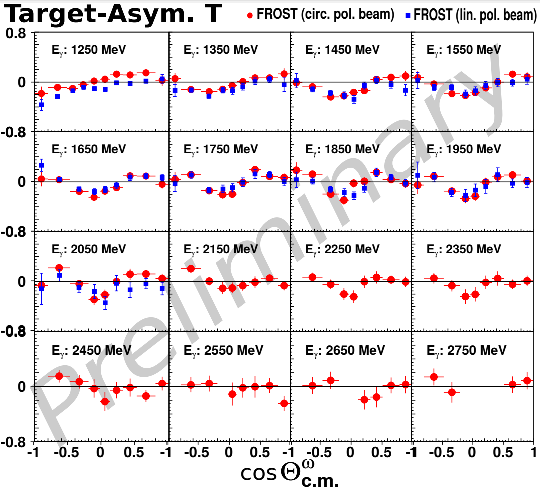


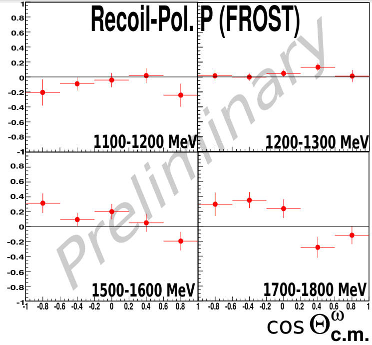
ω reconstructed from $\pi^+\pi^-(\pi^0)$

$$\sigma = \sigma_0[1 - \Sigma\ \delta_l \cos(2\phi)$$
$$+\Lambda\cos(\alpha)(-\delta_l \mathbf{H}\sin(2\phi) + \delta_\odot \mathbf{F})$$
$$-\Lambda\sin(\alpha)(-\mathbf{T} + \delta_l \mathbf{P}\cos(2\phi))]$$
$$-\Lambda_z(-\delta_l \mathbf{G}\sin(2\phi) + \delta_\odot \mathbf{E})]$$

$\delta_\odot(\delta_l)$: degree of beam pol.
Λ : degree of target pol.

First Measurements of T, P in $\vec{\gamma}\vec{p} \to p\omega$



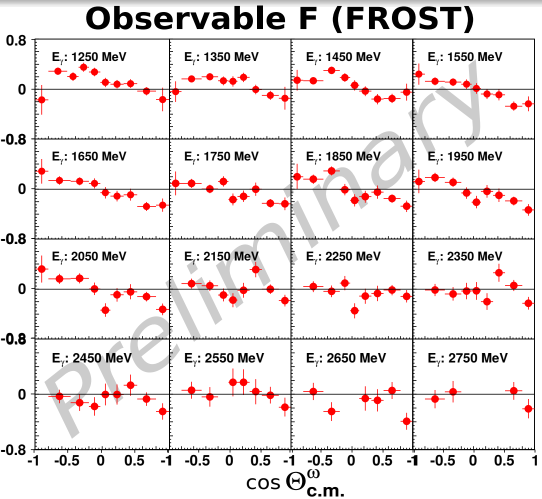


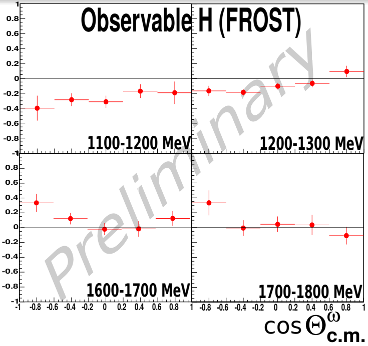
$$\sigma = \sigma_0[1 - \Sigma\ \delta_l \cos(2\phi)$$
$$+\Lambda\cos(\alpha)(-\delta_l \mathbf{H}\sin(2\phi) + \delta_\odot \mathbf{F})$$
$$-\Lambda\sin(\alpha)(-\mathbf{T} + \delta_l \mathbf{P}\cos(2\phi))]$$
$$-\Lambda_z(-\delta_l \mathbf{G}\sin(2\phi) \quad + \quad \delta_\odot \mathbf{E})]$$

The two experimental results on target asym. **T** from FROST agree well.

$\delta_\odot(\delta_l)$: degree of beam pol.
Λ : degree of target pol.

First Measurements of F, H in $\vec{\gamma}\vec{p} \to p\omega$



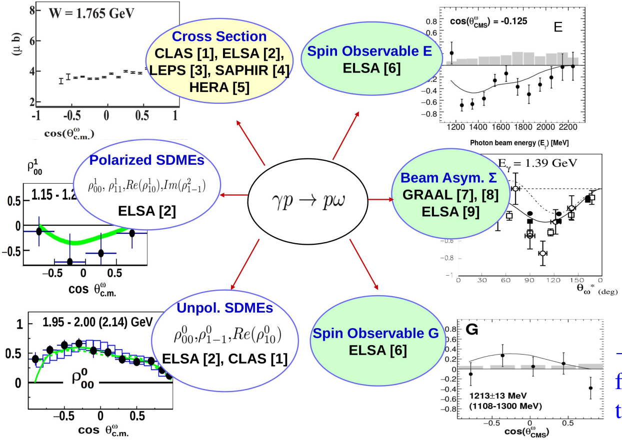


$$\sigma = \sigma_0[1 - \mathbf{\Sigma}\, \delta_l \cos(2\phi)$$
$$+\Lambda\cos(\alpha)(-\delta_l \mathbf{H}\sin(2\phi) + \delta_\odot \mathbf{F})$$
$$-\Lambda\sin(\alpha)(-\mathbf{T} + \delta_l \mathbf{P}\cos(2\phi))]$$
$$-\Lambda_z(-\delta_l \mathbf{G}\sin(2\phi) \quad + \quad \delta_\odot \mathbf{E})]$$

F and **H** are double-polarization observables.

$\delta_\odot(\delta_l)$: degree of beam pol.
Λ : degree of target pol.

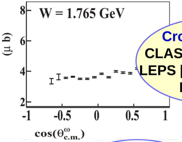
Published Results + New Results in $\gamma p \to p\omega$



+ High quality pol. SDMEs from CLAS, B. Vernarsky (CMU), to be published soon.

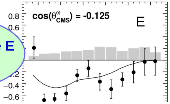
Published Results + New Results in $\gamma p \to p\omega$

Getting close to a 'complete experiment'!

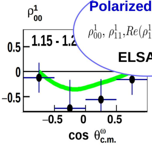


Cross Section
CLAS [1], ELSA [2], LEPS [3], SAPHIR [4]
HERA [5]

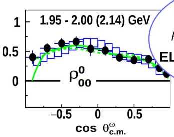
Spin Observable E
ELSA [6]



$\gamma p \to p\omega$

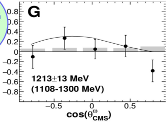


Polarized SDMEs
ρ^1_{00}, ρ^1_{11},$Re(\rho^1_{10})$,$Im(\rho^2_{1-1})$
ELSA [2]



Unpol. SDMEs
ρ^0_{00},ρ^0_{1-1},$Re(\rho^0_{10})$
ELSA [2], CLAS [1]

Spin Observable G
ELSA [6]



+ FROST (Prelim.) Results

Beam \ Target	Transversely Pol.	Longitudinally Pol.
Linearly Pol.	Σ, T, H, P	Σ, G
Circularly Pol.	F, T	E

+ High quality pol. SDMEs from CLAS, B. Vernarsky (CMU), to be published soon.

Results

Results in $\vec{\gamma}\vec{p} \rightarrow p\pi^+\pi^-$

Results in $\vec{\gamma}\vec{p} \rightarrow p\pi^+\pi^-$

- Allow the study of sequential decays of intermediate N^* and also $N^* \rightarrow p\rho$ decay but the large hadronic background makes it challenging.
- Reaction described using 2 planes (5 kinematic variables) $\rightarrow$ more spin observables than in single-meson photoproduction using polarized beam and target.

Results in $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$

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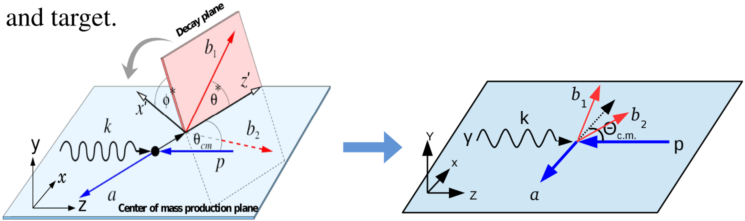


2 beam-pol. observables: I^s, I^c
Unlike only one (Σ observable) in single-meson photoproduction.

I^s vanishes, I^c survives.

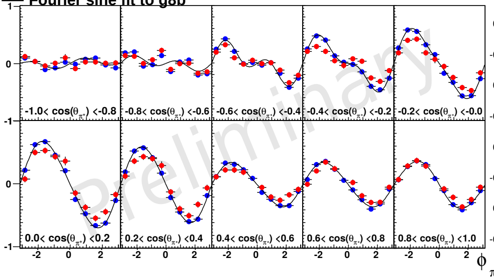
W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

Beam Asymmetry I^s in $\vec{\gamma} p \to p\pi^+\pi^-$

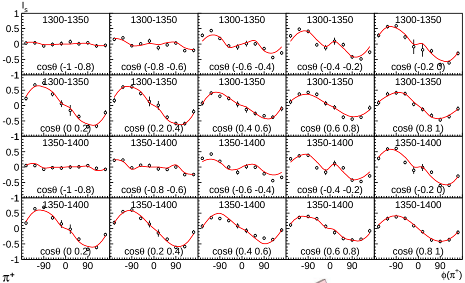
Example: $1.30 < E_\gamma < 1.40$ GeV (Total E_γ range covered: 0.7 - 2.1 GeV)

● FROST (preliminary) ● C. Hanretty *et al.* , CLAS-g8b run (in preparation for publication)

— Fourier sine fit to g8b

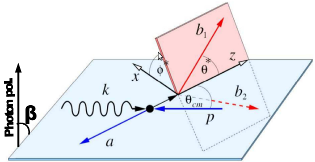


— BnGa fits to I^s, CLAS-g8b run



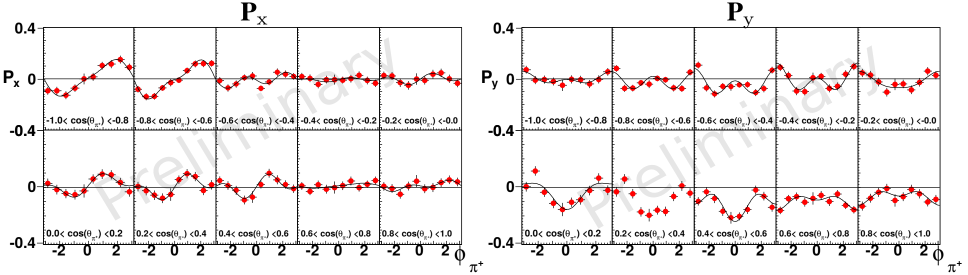
Good agreement between experiments

$$I = I_0\{\delta_l[I^s \sin(2\beta) + I^c \cos(2\beta)]\}$$



First Measurements of Target Asym. $P_{x,y}$ in $\gamma\vec{p} \to p\pi^+\pi^-$

Example: $1.3 < E_\gamma < 1.4$ GeV (Total E_γ range covered: 0.7 - 2.1 GeV)

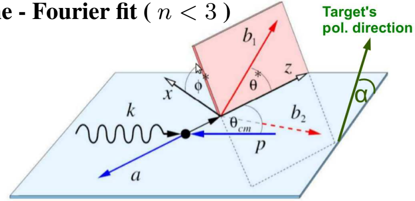


FROST g9b (lin. pol. beam) **Solid Line - Fourier fit ($n < 3$)**

3-dim. phase space: $(E_\gamma, \phi^*_{\pi^+}, \cos\theta^*_{\pi^+})$

$$I = I_0[1 + \Lambda\cos(\alpha)P_x + \Lambda\sin(\alpha)P_y]$$

Λ : degree of target pol.



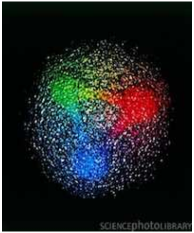
Outline

1. Introduction
   - Motivation

2. Data Analysis and Results
   - $p\omega$ Reaction, Single- & Double-Polarization Observables
   - $p\pi^+\pi^-$ Reaction, Single Polarization Observables

3. Summary and Outlook

Summary and Outlook



- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances. These decay modes have mostly remained unexplored in the past.
- **Many first time measurements of single- and double-polarization observables from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.
  - **The new high quality CLAS results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
  - The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

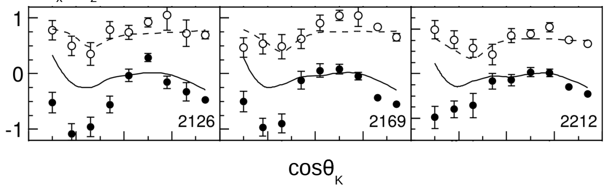
This work is supported by
DOE# DE-FG02-92ER40735

Thank You !
Any Questions ?

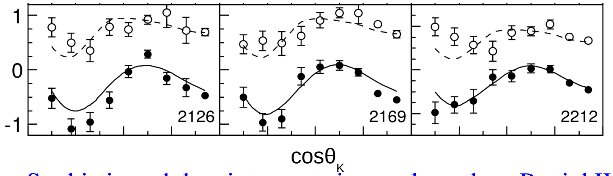
Why are Spin Observables Important?

[1] R. Bradford *et al.* (CLAS), PRC **75**, 035205 (2007), Observables C_x, C_z from $\vec{\gamma} p \to K^+ \vec{\Lambda}$
[2] Fits: BnGa Model, V.A. Nikonov *et al.*, Phy. Lett. B **662**, 245 (2008)

C_x, C_z Fits without N(1900)3/2$^+$ resonance



C_x, C_z Better Fit Results with N(1900)3/2$^+$!

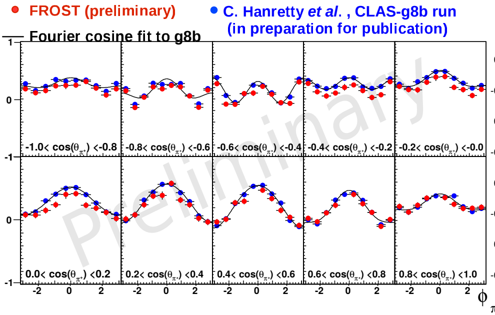


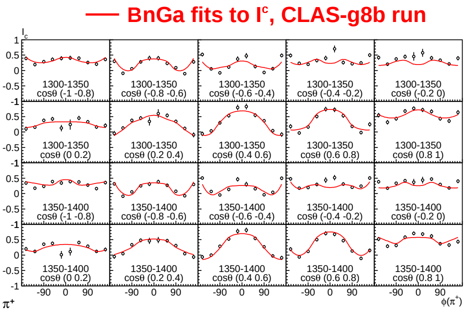
N^*	J^P $(L_{2I,2J})$	2010	2012
$N(1440)$	$1/2^+$ (P_{11})	****	****
$N(1520)$	$3/2^-$ (D_{13})	****	****
$N(1535)$	$1/2^-$ (S_{11})	****	****
$N(1650)$	$1/2^-$ (S_{11})	****	****
$N(1675)$	$5/2^-$ (D_{15})	****	****
$N(1680)$	$5/2^+$ (F_{15})	****	****
$N(1685)$			*
$N(1700)$	$3/2^-$ (D_{13})	***	***
$N(1710)$	$1/2^+$ (P_{11})	***	***
$N(1720)$	$3/2^+$ (P_{13})	****	****
$N(1860)$	$5/2^+$		**
$N(1875)$	$3/2^-$		***
$N(1880)$	$1/2^+$		**
$N(1895)$	$1/2^-$		**
$N(1900)$	$3/2^+$ (P_{13})	**	***
$N(1990)$	$7/2^+$ (F_{17})	**	**
$N(2000)$	$5/2^+$ (F_{15})	**	**
~~$N(2080)$~~	D_{13}	**	
~~$N(2090)$~~	S_{11}	*	
$N(2040)$	$3/2^+$		*
$N(2060)$	$5/2^-$		**
$N(2100)$	$1/2^+$ (P_{11})	*	*
$N(2120)$	$3/2^-$		**
$N(2190)$	$7/2^-$ (G_{17})	****	****
~~$N(2200)$~~	D_{15}	**	
$N(2220)$	$9/2^+$ (H_{19})	****	****

Sophisticated data interpretation tools such as Partial Wave Analysis and Phenomenological models are required to identify the contributing resonances.

Beam Asymmetry I^c in $\vec{\gamma} p \to p\pi^+\pi^-$

Example: $1.30 < E_\gamma < 1.40$ GeV

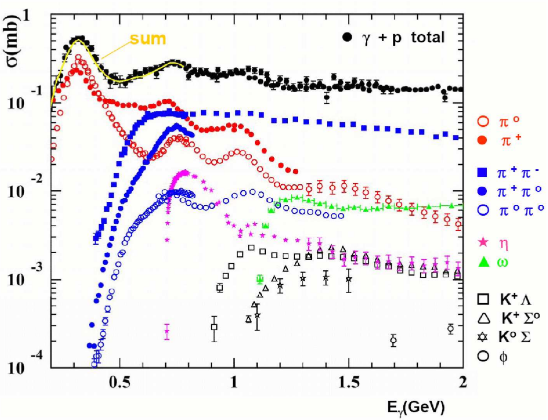




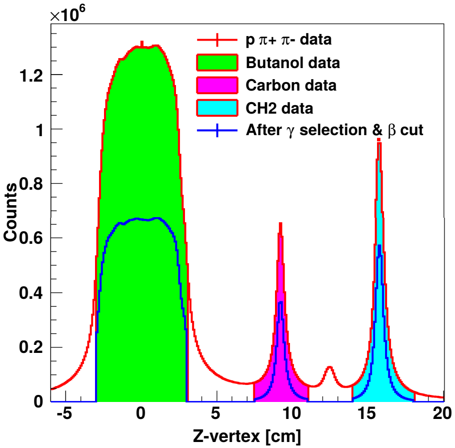
Good agreement between experiments

$$I = I_0\{\delta_l[I^s\sin(2\beta) + I^c\cos(2\beta)]\}$$

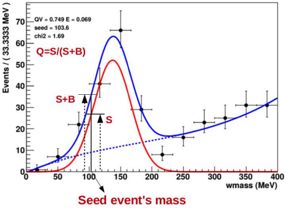
Photoproduction Cross Section



Vertex cut


×10^6
p π+ π- data
Butanol data
Carbon data
CH2 data
After γ selection & β cut
Counts
0
0.2
0.4
0.6
0.8
1
1.2
-5
0
5
10
15
20
Z-vertex [cm]

Event-Based Qfactor Method with Likelihood Fits



- **A multivariate analysis -** For each event ("seed event"), find N nearest neighbors in 4-D kinematic phase space $(E_\gamma, \theta^*, \phi^*, cos(\theta_p)^{c.m.})$. Plot mass distribution of the $N+1$ events and fit.
- Since N is small (300), use ML method to fit the mass distribution.
  $L = \prod_i [f^{Signal}(m_i, \alpha) + f^{Bkg}(m_i, \beta)]$
  $\mathbf{Q_{seed-event}} = \frac{f^{Signal}(m_0, \alpha^{best})}{[f^{Signal}(m_0, \alpha^{best}) + f^{Bkg}(m_0, \beta^{best})]}$,
  m_0- seed event's mass.
- **Computation time reasonably minimized-** fits 10,000 events in 30 min.